National Spent Nuclear Fuel Program

Advanced Neutron Absorber Development

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Providing for safe, efficient disposition of DOE spent nuclear fuel

Outline

- Ni-Cr-Mo-Gd Alloy Development
- Results
  - Microstructural Features and Corrosion Performance Studies
  - Plate Mechanical Properties
  - Welding Trials
  - Criticality Safety (Neutron Absorption) Experiments
- ASME/ASTM Status
- Summary

Project Overview

Problem:

- Some types of USDOE spent nuclear fuel (SNF) contain highly enriched uranium
- Final disposition of this SNF the repository may require criticality control during the regulatory period

Approach:

- SNF will be packaged in standardized canister with baskets fabricated from thermal neutron absorbing materials

Benefits:

- DOE SNF is critically safe under fully flooded conditions
- Decreased number of SNF packages going to repository with reduced handling and materials costs.

Project Summary

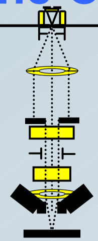
- ASTM Material Specifications for Ni-Cr-Mo-Gd Alloy is in final approval stage
- Developing complete mechanical properties dataset
- Continuing mechanical properties/ microstructure/corrosion/weldability investigations
- Continuing hot working evaluations
- Initiating ASME code actions

Tasks

- Develop a nickel based corrosion resistant alloy with a gadolinium addition. Gadolinium has a high thermal neutron absorption cross section.
- Determine effect of alloy microstructure on corrosion performance, mechanical properties, and thermal neutron absorption
- Develop an American Society for Testing and Materials standard
- Perform mechanical properties measurements for acceptance in Section II of the ASME Code

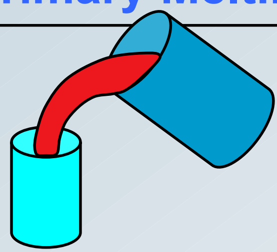
Project Workflow

Define Compositions



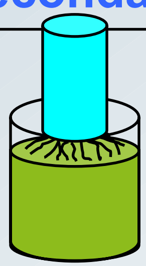
- Laboratory Evaluations
- Fe-Ni-Cr-Gd
- Ni-Cr-Mo-Gd

Primary Melting and Casting



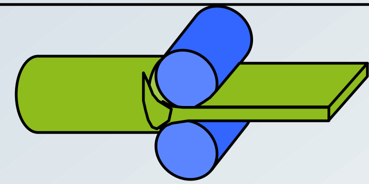
Vacuum Induction Melting (VIM)

Secondary Melting/Refining



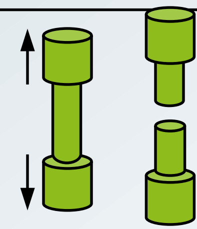
Vacuum Arc Remelting (VAR)

Hot Working/Rolling



- Hot Ductility
- Forging
- Rolling

Properties Testing



- Tensile
- Charpy Impact
- Corrosion
- Weldability
- Neutronics

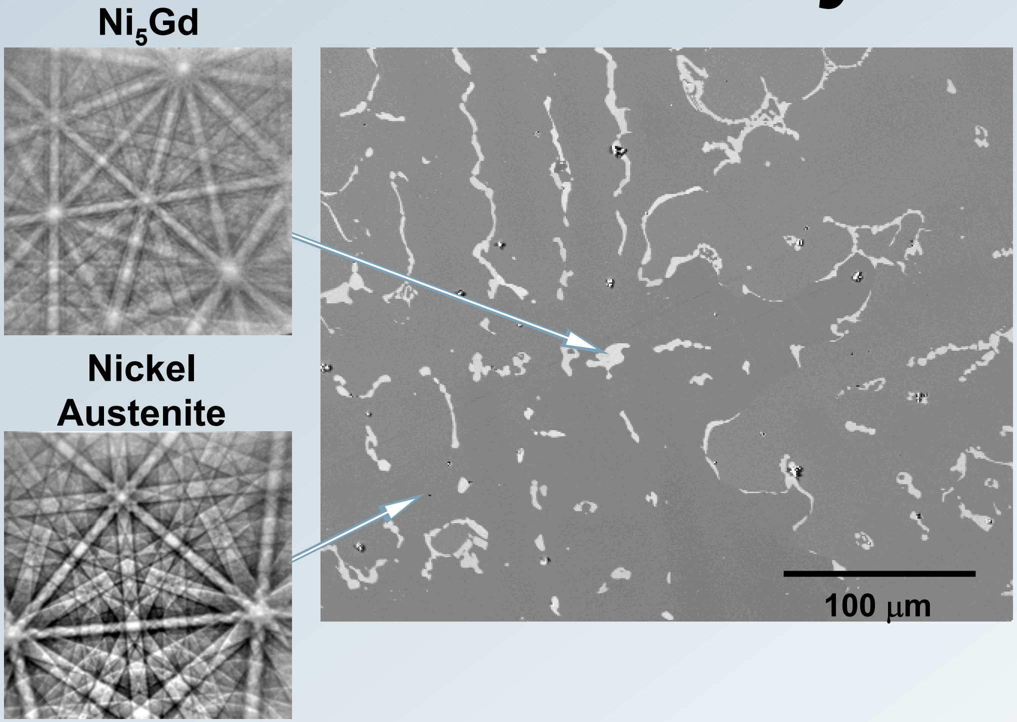
Codes and Standards

- ASTM Specification
- ASME Code Section III
- Commercialization

Heat Chemistries

Element	Heat M322 VIM/VAR	Heat M326 VIM/VAR	Heat M327 VIM/VAR	HVO 0182 VIM
Al	0.005	Not reported	Not reported	Not reported
C	<0.001	0.006	<0.001	0.031
Co	<0.001	0.009	0/003	Not reported
Cr	14.93	14.71	21.01	14.71
Fe	0.028	0.025	0.0032	Not reported
Gd	2.38	2.00	1.98	1.5
Mg	<0.001	0.002	0.002	Not reported
Mn	<0.001	<0.001	<0.01	0.30
Mo	14.71	14.53	14.32	14.76
Ni	Balance	Balance	Balance	67.77
S	<0.001	<0.001	0.002	0.0014
Si	<0.01	0.013	0.018	0.12

Typical as-cast microstructure of Ni-Cr-Mo-Gd alloys



Element	Nominal ASTM Chemistry	Gadolinide
Mo	14.9	0.69
Cr	15.1	2.00
Fe	1.0 max	0.04
Co	0.3 max	---
C	0.010 max	---
Si	0.08 max	0.08
Mn	0.5 max	0.00
P	0.01 max	---
S	0.005 max	---
Ni	bal	63.13
N	0.010 max	---
Gd	2.0	35.26

- Composition of gadolinide was similar for a range of melt chemistries - No Gd observed in matrix
- Matrix composition can be controlled by adjustment of bulk chemistry

Microstructural Features and Corrosion Performance

- The Ni-Cr-Mo alloys are resistant to corrosion by oxidizing and reducing environments. Alloy 22 (waste package outer barrier material) is an alloy of this type.
- There is no solubility of Gd in austenite matrix of Ni-Cr-Mo alloys
- A Gd rich, eutectic, secondary phase forms - $(Ni,Cr)_5Gd$
- This second phase may be selectively attacked in some projected YMP in-drift environments
- The two phase structure differentiates these alloys from other Ni-Cr-Mo alloys

Hot working of up to 2.4 wt% Gd alloy ingots successful

VAR Ingot-as cast

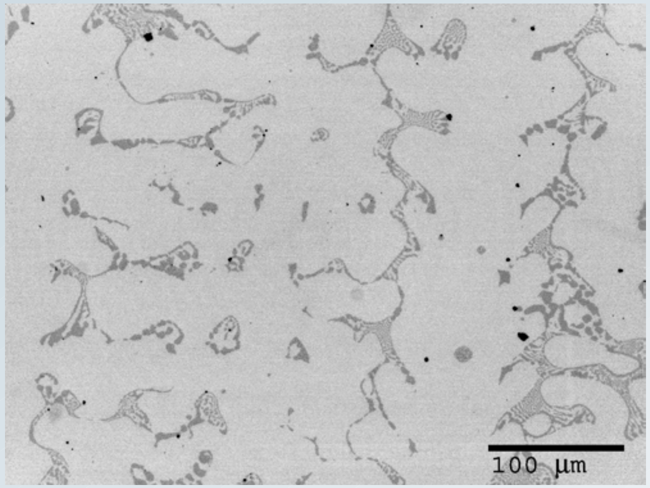
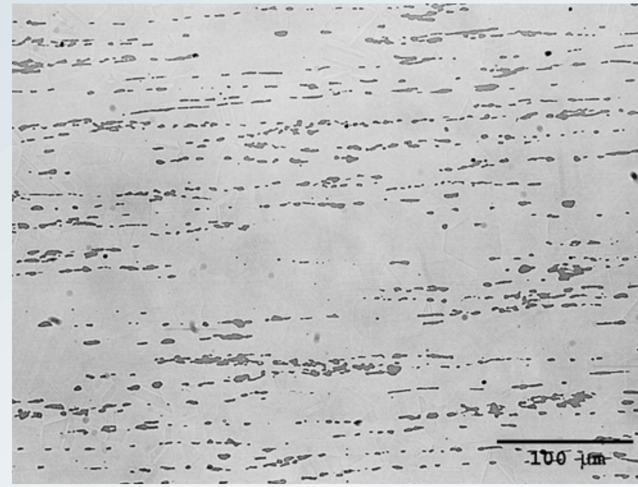
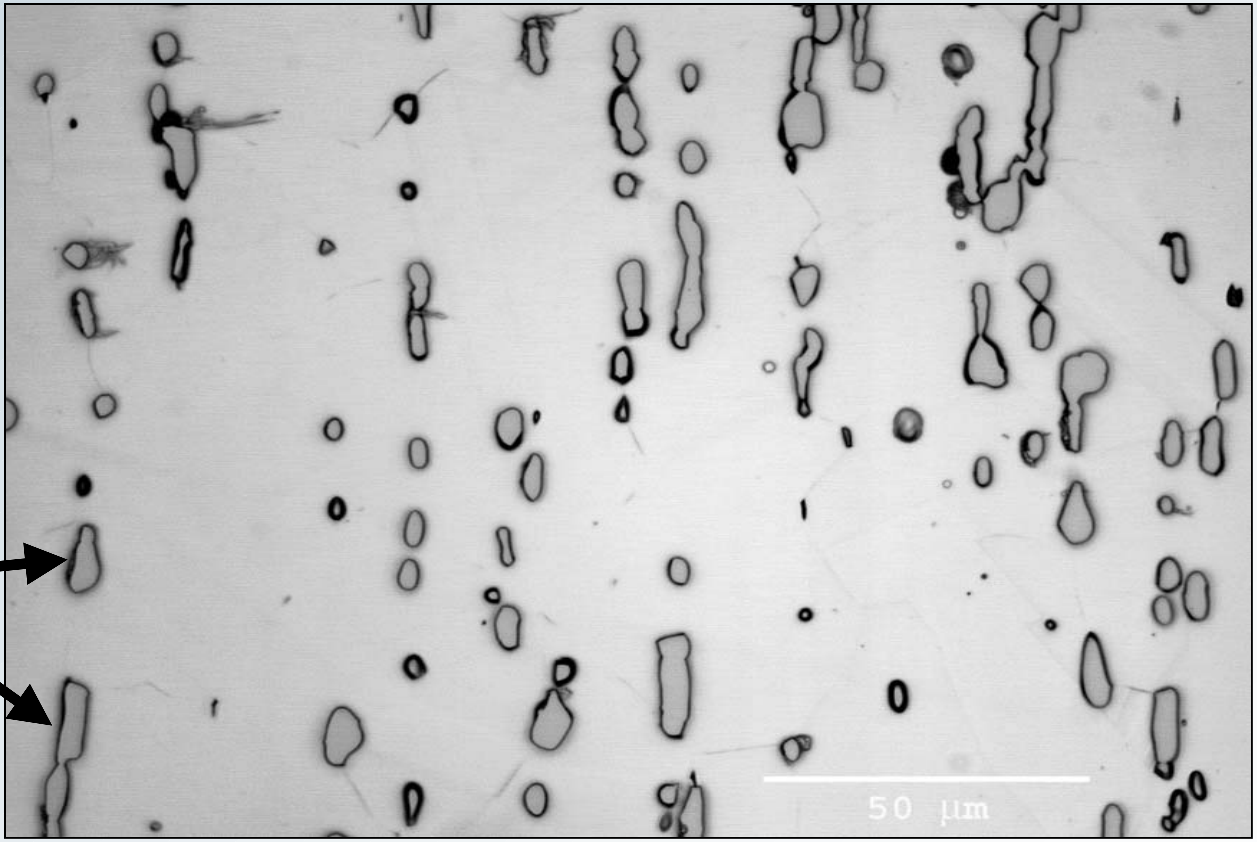


Plate (L-S orientation)



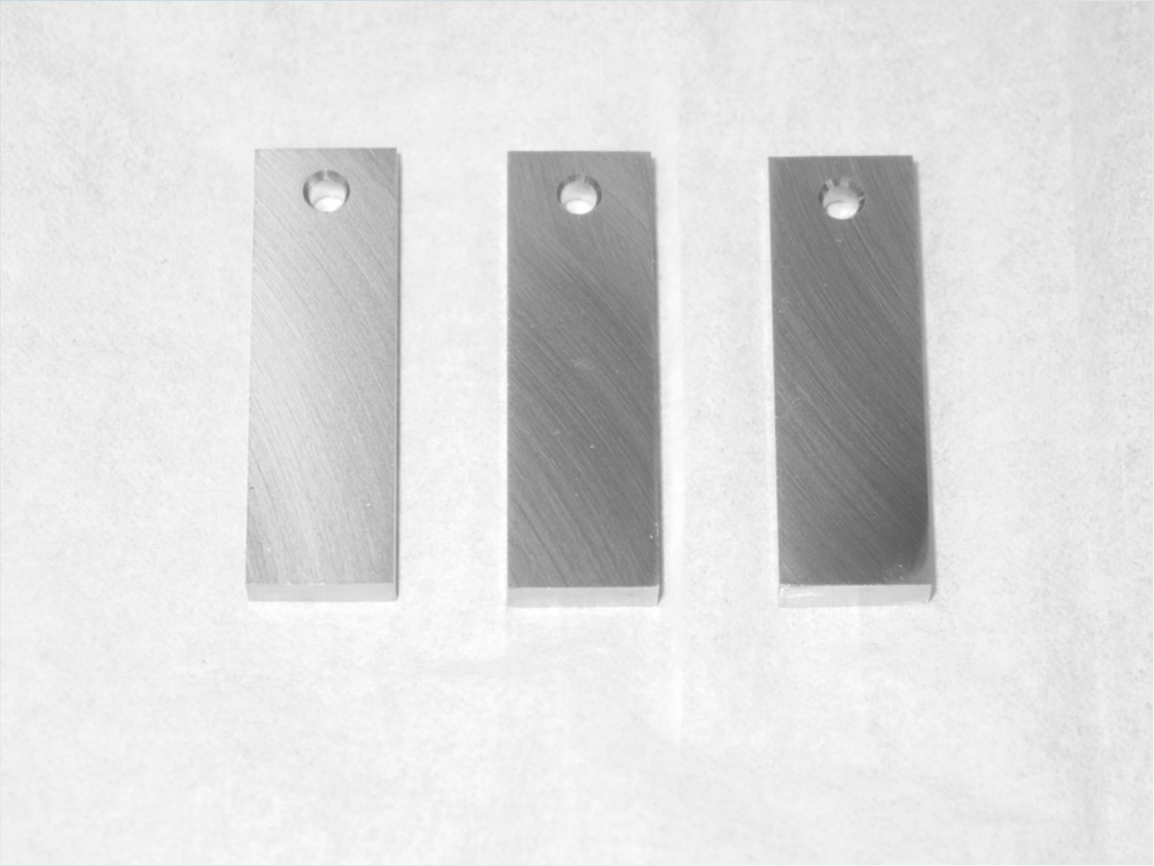
- Gadolinide distribution evolves during hot working
- Some surface cracking was experienced
- Differences between various heats have been observed
- Further optimization of hot working procedures is underway

LOM of Heat M327



$(Ni,Cr)_5Gd$

Immersion Test Results



Conditions-Heat M322

- **J-13, 30°C**
- **6720 hours**

Corrosion rate
20 nm/yr

Conditions-Heat M322

- **50X J-13, 30°C**
- **5424 hours**

Corrosion rate
89 nm/yr

Notes:

- ***1 nm = 1 $\times$ 10^{-9} m***
- ***Alloy 22 rate Is 15 nm/yr in J-13***

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Electrochemical Corrosion Test Results

- Potentiodynamic test results show acidic chloride solutions and J-13 will initially remove gadolinide $(Ni,Cr)_5Gd$ and Gadolinium Oxide(Gd_2O_3) that intersect the surface.
  - Alloy will then repassivate and experience a very low corrosion rate
  - Localized corrosion performance is better than a borated stainless steel in acidic, aggressive environments
  - General corrosion performance should approach that of alloy C-4
  - Accelerated test

Mechanical Properties of Recent Heats

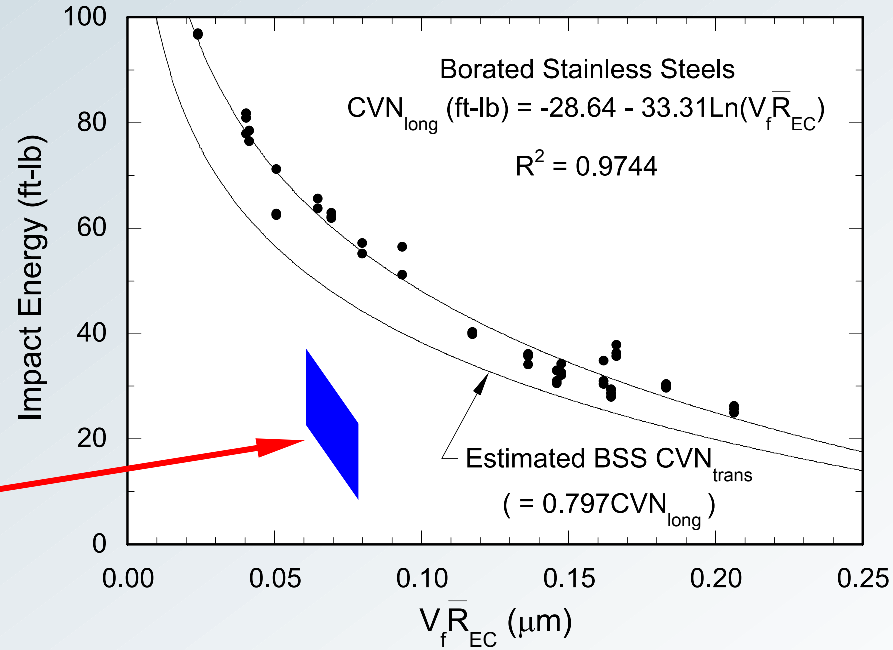
	Heat	Orientation	YS (ksi)	UTS (ksi)	Elong. (%)	RA (%)	Impact Energy (ft-lb)	Lateral Exp (inch)
Straight Rolled	326	Trans	60.0	104.7	22.3	18.6	14.2	---
	(1200°C/4hr/WQ)	Long	60.9	118.5	46.1	35.2	27.3	---
	327	Trans	61.4	108.1	24.1	21.0	16.3	---
	(1200°C/4hr/WQ)	Long	60.7	115.7	51.1	38.5	33.2	---
Cross Rolled	HV0182	Long*	80.7	125.0	39.3	35.3	19.7	0.015
	(As Rolled)	Trans*	86.3	116.7	22.7	21.3	15.7	0.012
	HV0182	Trans*	54.8	104.0	29.0	22.0	23.3	0.020
	(1093°C/4hr/WQ)	Long*	53.8	114.3	44.3	35.3	38.7	0.033

*Relative to primary rolling direction

- Optimization of hot working schedules appears to be successful - current evaluations include:
  - Multi-axis forging
  - Rolling temperature
  - Reduction per pass
  - Cross rolling
  - Post rolling annealing

Mechanical Properties - Comparison with BSS

- Correlation for borated stainless steels based on data for both A and B Grades



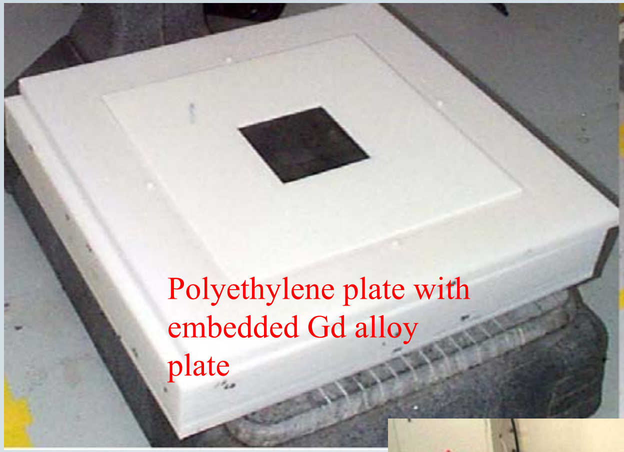
Range of current Gd alloy values

- Higher strength of Ni alloy matrix may contribute to disparity
- However, it seems likely that further improvements in alloy cleanliness and gadolinide distributions will significantly improve properties

Criticality Safety (Neutron Absorption) Experiments

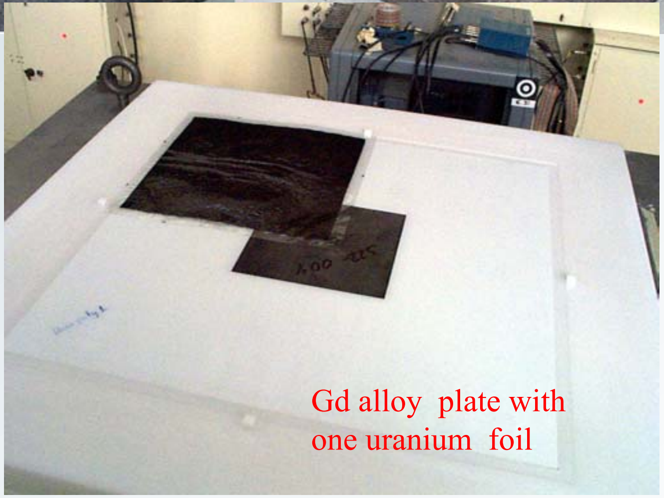
- Experiments were performed at the Los Alamos National Laboratory Criticality Experiments Facility
- The experiment consisted of interlaying highly enriched uranium foils with polyethylene and Gd alloy plates that simulate a fully moderated configuration in a critical system
- Initial measurements and calculations suggest that the negative worth of Gd alloy plates is about 8.8$ of reactivity.
- Calculated negative worth of an equivalent volume of borated stainless steel plate (1.7% B) is 6.4$ of reactivity.
  - Ni-Cr-Mo-Gd alloy is a more effective thermal neutron absorber
- Computational results tend to agree well with experimental results

Gd Alloy Plates in Experimental Setup



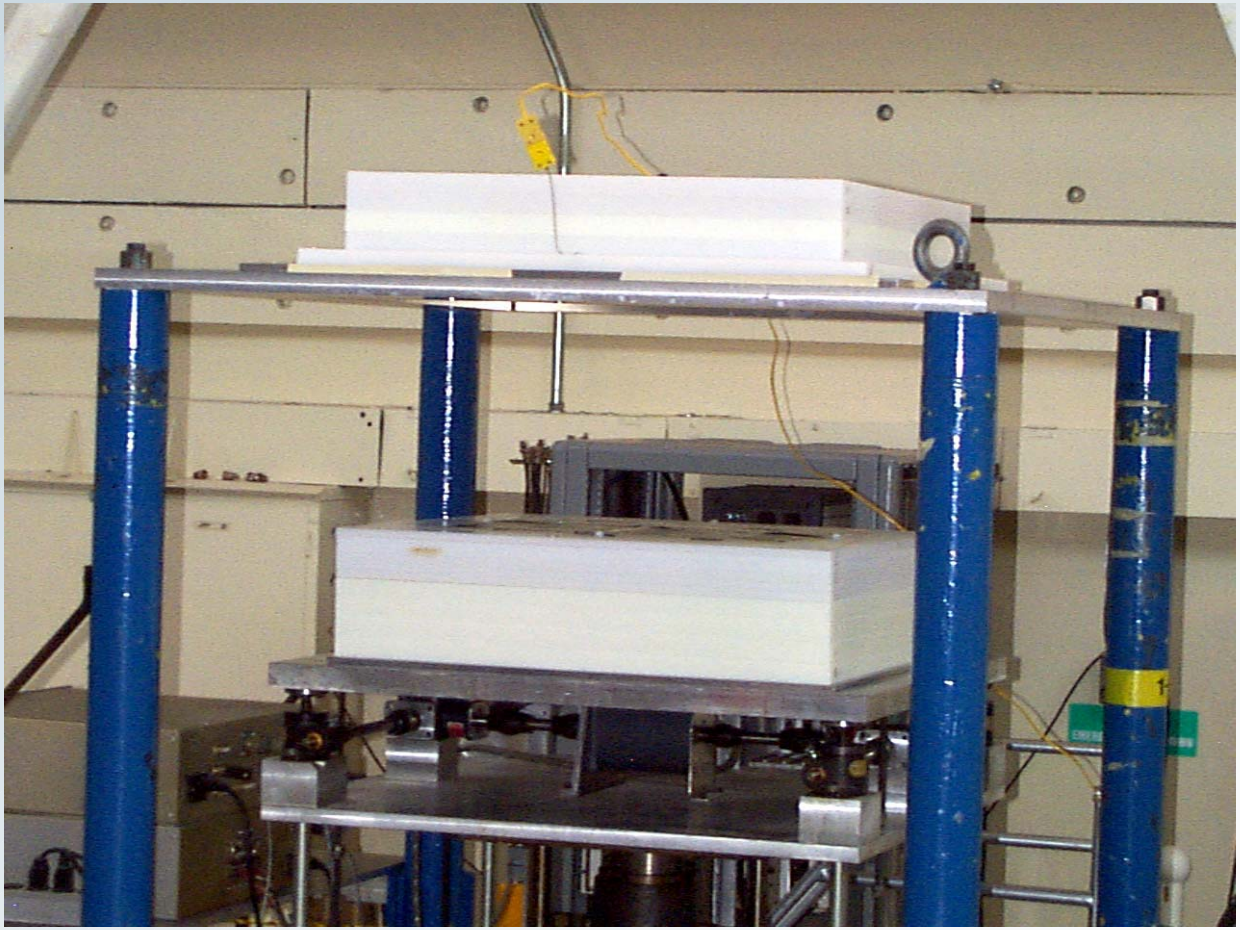
Polyethylene plate with embedded Gd alloy plate

Gd alloy plate and polyethylene insert



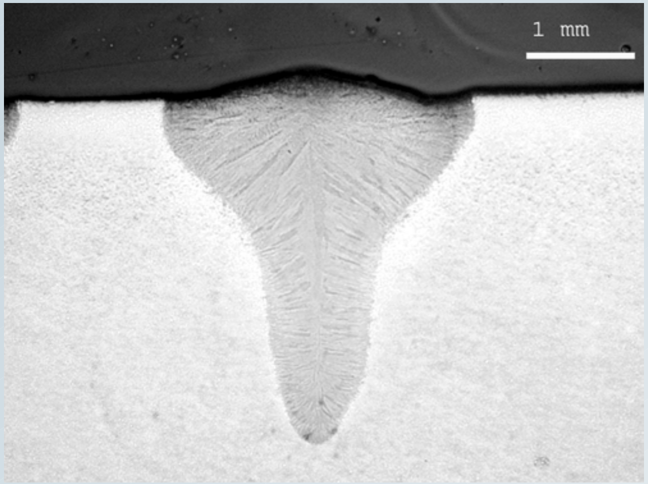
Gd alloy plate with one uranium foil

Criticality Test Setup

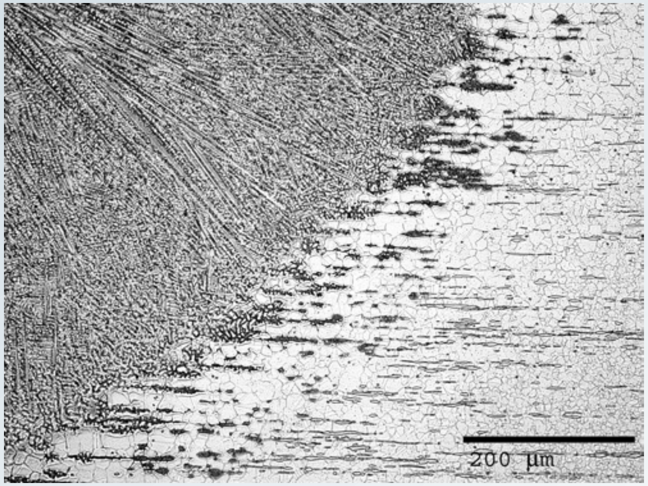


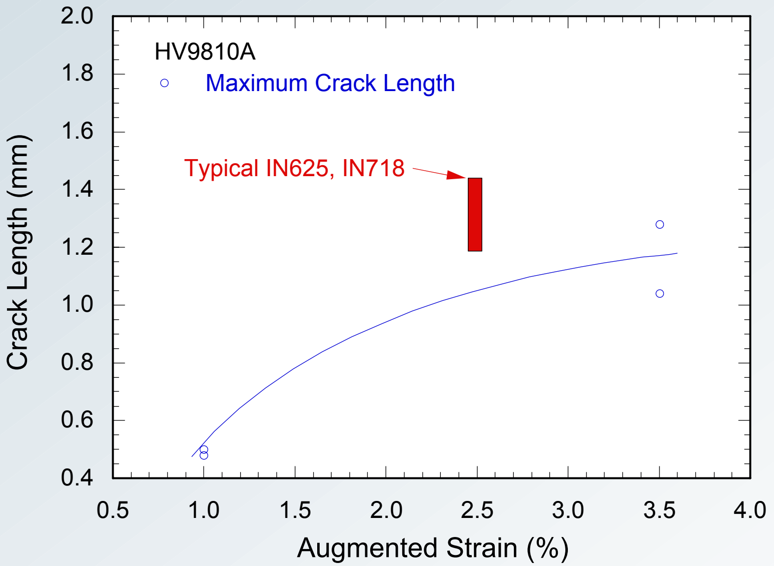
Welding Trials and Weldability

E-beam weld



GTA weld fusion boundary





- **Initial electron beam and gas-tungsten arc welding trials are promising**
- **Varestraint tests indicate response is favorable in comparison with other commonly welded Ni-based alloys**
- **Behavior is commensurate with melting temperature range**

Codes and Standards Status

- ASTM Specification for 2 wt% N06455 type alloy balloted at main committee (ASTM B02-Non-Ferrous Alloys):
  - Ballot closes on January 23, 2004
  - Expected to be published in ASTM Volume 2.04 in May 2004
- Alloy neutronics measured (at LANL) and approved values incorporated into *International Handbook Of Evaluated Criticality Safety Benchmark Experiments*
- ASME Code Case submission awaiting hot working trials and finalization of data package
  - Submission expected by end of FY04

Summary

- Ni-Cr-Mo-Gd alloys can be made with conventional ingot metallurgy techniques.
- The alloys will meet all performance requirements
  - Mechanical properties will meet ASME requirements in as-welded condition (transportation issue)
  - Criticality control during regulatory period is assured based on corrosion tests
  - Thermal neutron absorption performance of prototype alloys is exceptional and consistent with published data